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Numerical Investigations into the Nonsinusoidal Motion Effects on Aerodynamics of a Pitching Airfoil

Kun Lu[a], Yonghui Xie[b,*], Di Zhang[c]

[a,b]*School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi Province, 710049, China*
[c]*Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi Province, 710049, China*

Abstract

The growing applications of wind turbine impose the need for accurate flow solutions of airfoils with different pitching motions. In this paper an adjustable parameter K is employed to realize various nonsinusoidal motions and the effects of nonsinusoidal motion on pitching airfoil aerodynamics of a 2-D NACA0012 airfoil are numerically studied at Re=1.35×10^5. The nonsinusoidal motion effects on the instantaneous force coefficients and flow patterns are studied at different unsteady parameters (amplitude of oscillation, θ; reduced frequency, k). The results reveal that the nonsinusoidal motion noticeably affects the instantaneous force coefficients, maximum lift and drag coefficients. Besides, the formation of leading edge vortices and flow structures are also affected by the nonsinusoidal motion.

Keywords: Pitching airfoil; Nonsinusoidal motion; Unsteady aerodynamics; Navier–Stokes simulations

1. Intoduction

In recent years pitching airfoil aerodynamics has drawn much attention because of its significance in applications for the wind turbine design. It has been the subject of numerous experimental and numerical investigations [1-5]. The researchers mainly investigated the factors that affect the aerodynamic performance. However, most of the work only studied the airfoil in sinusoidal pitching motion, and little attention was paid to the nonsinusoidal motion effects on aerodynamics of a pitching airfoil.

The purpose of this paper is to study the effect of nonsinusoidal motion on the aerodynamics performance of a pitching NACA0012 airfoil. Simulations are carried out at different pitching amplitude θ and reduced frequency k ($k=\pi fc/U_\infty$, where f is the pitching frequency, c is the airfoil chord length and U_∞ is the free stream velocity). All the simulations are conducted at Re=1.35×10^5, which is appropriate to the applications of rotorcraft and urban Vertical Axis Wind Turbines (Wang et al. [4]).

2. Numerical method

* Corresponding author. Tel.: +86-29-82664443; fax: +86-29-82664443.
E-mail address: yhxie@mail.xjtu.edu.cn.

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In this paper the commercial CFD package ANSYS CFX 11.0 with an unsteady incompressible and viscous flow solver is applied to simulate the unsteady flow field around a pitching airfoil. The numerical method used in this paper is the same as that used in our previous study Lu et al. [5], where the validation studies for the numerical method used can also be found. The pitching motion is given by:

$$\begin{cases} \alpha(t) = \alpha_0 + \dfrac{\theta \sin^{-1}\left[-K\sin(2\pi ft)\right]}{\sin^{-1}(-K)}, -1 \le K < 0 \\ \alpha(t) = \alpha_0 + \theta\sin(2\pi ft), K = 0 \\ \alpha(t) = \alpha_0 + \dfrac{\theta \tanh\left[K\sin(2\pi ft)\right]}{\tanh K}, K > 0 \end{cases} \quad (1)$$

where α_0 is the mean angle of attack and is chosen as 0° [5]. The pitch axis is located at 1/4 of chord from leading edge [5]. The pitching profile can be changed from a sawtooth wave (K= -1) to a square wave ($K\to\infty$) by increasing K. Fig. 1 shows the waveform shapes for K= -1, -0.95, 0, 1 and 1.5 at θ=7.5°.

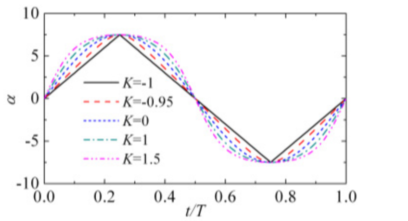

Fig. 1. Variation of instantaneous angle of attack in one period at θ=7.5°.

3. Results and discussion

In this paper two pitch angles θ=7.5° and 15° with α_0=0° and two different reduced frequencies k=0.1 and 0.2 are used. Besides, four K of -0.95, 0, 1 and 1.5 are chosen for each case. Fig. 2(a) shows the lift force coefficient C_l and drag force coefficient C_d versus α for the case of θ=7.5° and k=0.1. As observed the effect of K on C_l is quite limited and no notable change in C_l is caused by the nonsinusoidal motion. Additionally, K has little effect on the lift curve slopes and hysteresis loop width. While the variation of C_d with α is notably affected by the nonsinusoidal motion. As observed the increasing K leads to a notable decrease in the minimum drag coefficient ($C_{d,\min}$) and a slight decrease in the maximum drag coefficient ($C_{d,\max}$). Moreover, as K increases the drag coefficient hysteresis loops show the trend of being broadened. According to Equation (1) the variation of pitch rate in a cycle depends on K. Visbal and Shang [1] reported that for a pitching airfoil the forces and vortical structures depend on pitch rate. Thus we can conclude that because of the change in pitch rate caused by K, the drag coefficient hysteresis loops are broadened as K increases.

Fig. 2(b) shows C_l and C_d versus α for the θ=7.5° and k=0.2 case. According to the comparison between Fig. 2(a) and Fig. 2(b), it is found that the lift coefficient hysteresis loops for k=0.1 and k=0.2 cases show the similar trend, as well as drag coefficient hysteresis loops. This is because at each K these two cases share the same pitching profile and no large-scale flow separation occurs at θ=7.5°. Besides, $C_{d,\max}$ increases with pitching frequency and $C_{d,\min}$ decreases with pitching frequency. Besides, k does not noticeably change the pattern of hysteresis loops, and this agrees with the study by Amiralaei et al. [3]. At k=0.2 the nonsinusoidal motion has more effect on the variation of C_l than that at k=0.1. The lift coefficient hysteresis loops is notably broadened by the increasing K between α=-4° and 4°. For the drag coefficient hysteresis loops the effect of increasing K at k=0.2 is quite similar with that at k=0.1.

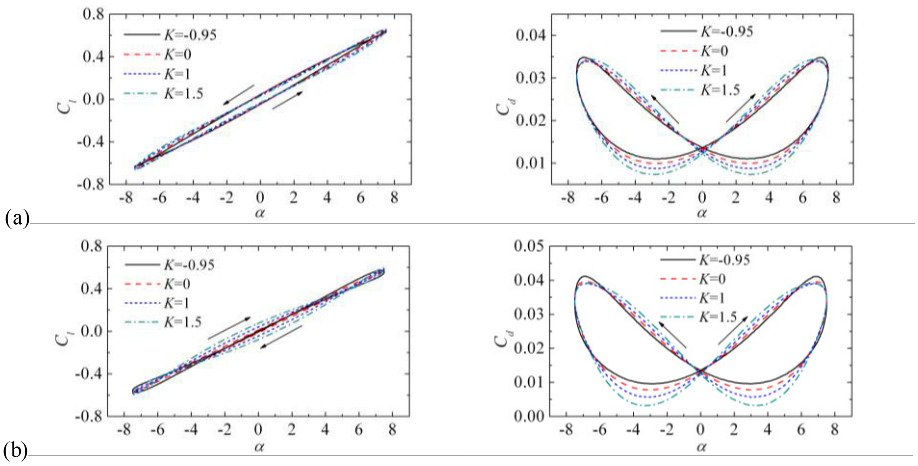

Fig. 2. Lift force coefficient C_l and drag force coefficient C_d versus α for the case of θ=7.5°: (a) k=0.1; (b) k=0.2.

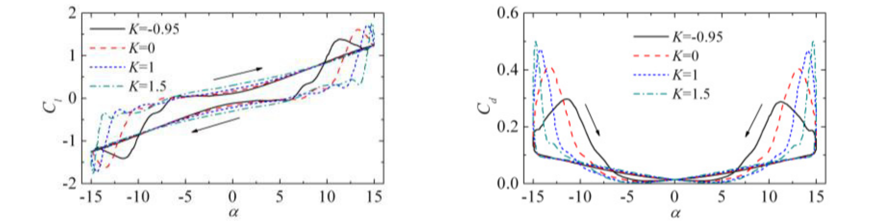

Fig. 3. Lift force coefficient C_l and drag force coefficient C_d versus α for the case of d=15° and k=0.1.

The variation of C_l and C_d with angle of attack for θ=15° and k=0.1 is shown in Fig. 3. Because of the leading-edge type of dynamic stall the hysteresis loops are very different from those of θ=7.5° case. Basically the variation of C_l with α share the same trend for each K, as well as C_d. As the leading edge vortex (LEV) develops in the downstroke, the large scale LEV induces a notable drop in C_l and a significant increase in C_d between α=10° and 15°, and these agree with the dynamic stall phenomenon. Then the lift curve slope becomes lower, corresponding to flow reattachment process. As observed the increasing K leads to an earlier decrease in C_l and makes the flow reattachment process happens at a higher α. Besides, the increasing K also makes the decrease of occurs at a higher α. The lift lift coefficient hysteresis loops shows the trend of being broadened as K increases. As discussed in the cases of θ=7.5°, this can also be attributed to the variation in pitch rate, which notably affects the force coefficients and vortical structures of a pitching airfoil (Visbal and Shang, [1]). Additionally, the increasing K induces a noticeable increase in the maximum lift and drag coefficient.

In the present study K dominates the motion of pitching airfoil. Thus, nonsinusoidal motion may affect the aerodynamic force by influencing the flow development around the airfoil. Fig. 4 and 5 show the streamlines for different angles of attack in the downstroke at K=0 and K=1.5 in θ=15° and k=0.1 case respectively. As observed K plays a significant role on the LEV development. At K=0, as the airfoil approaches α=15°, a LEV occurs at the leading edge (Fig. 4 (a)) and then it convects over the airfoil (Fig. 4(b)). However, at K=1.5 the LEV has convected downward from the leading edge at α=15° (Fig. 5(a)). At α=14.7° the LEV has reached the trailing edge for K=1.5. While at K=0 the LEV has just reached the mid-chord region at α=14.7°. At α=9.5° and K=0 the rolling-up trailing edge vortex is detached from the airfoil. While at K=1.5, the vortices has moved to the downstream of trailing edge at α=9.5° in the downstroke. As a result, at a larger K the LEV occurs at a lower α and flow reattachment process begins at a higher α, making the decreasing in C_d happens at a higher α (Fig. 3). This is because the higher K leads to a longer time for the airfoil to pitch to α=14.7° and 9.5° from α=15° in the downstroke. Thus the lower K results in less time available for vortex formation and convection over the airfoil surface.

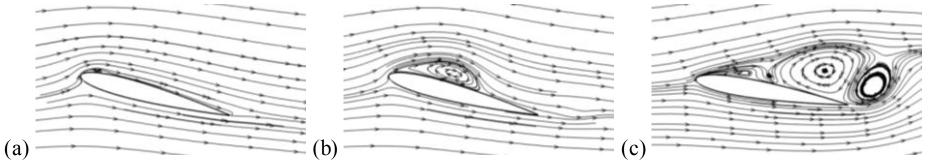

Fig. 4. Flow streamlines for θ=15° and k=0.1 at K=0: (a) 15°; (b) 14.7°, downstroke; (c) 9.5°, downstroke

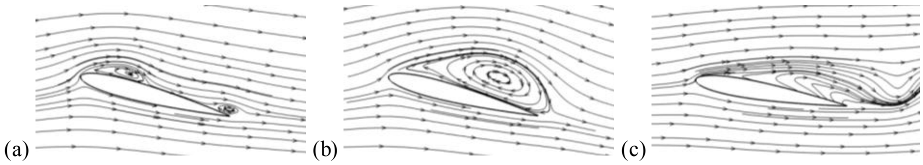

Fig. 5. Flow streamlines for θ=15° and k=0.1 at K=1.5: (a) 15°; (b) 14.7°, downstroke; (c) 9.5°, downstroke.

4. Conclusion

In this paper the effects of nonsinusoidal motion on pitching airfoil aerodynamics are studied by numerical simulations for 2-D flow around a NACA0012 airfoil at Re=1.35×10^5. Four types of pitching profiles are chosen and the effects of nonsinusoidal motion on the instantaneous force coefficients and flow patterns are fully studied. The results show that the instantaneous force coefficients, aerodynamic force peak values, and hysteresis loop width are noticeably affected by K. It is also found that K has a significant impact on the flow structures and the development of leading edge vortex. At a larger K the leading edge vortex occurs at a lower angle of attack α and flow reattachment process begins at a higher α.

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Biography

Kun Lu (1988-) is a Ph.D student of School of Energy and Power Engineering in Xi'an Jiaotong University. He mainly studies the oscillating airfoil aerodynamics for its applications in micro-aerial vehicles (MAVs) design, wind turbine and other energy extraction devices.